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A measurement of the ^{10}Be/^{9}Be ratio above 1.0 GeV/nucleon: Results from the 1998 flight of ISOMAX

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Abstract. The Isotope Magnet Experiment, ISOMAX, was a balloon-borne instrument designed to measure the isotopic composition of the light elements in cosmic rays ($3 \leq Z \leq 8$), with a particular emphasis on the measurement of the radioactive isotope ^{10}Be. ISOMAX, flown in August 1998 from Lynn Lake, Manitoba, Canada, measured isotope mass with excellent resolution by combining velocity measurements from a time-of-flight (TOF) system and two Cherenkov detectors with magnetic rigidity (charge/momentum) measurements from the magnetic spectrometer. Velocity from the TOF can be used to resolve isotopes of beryllium from ~0.2 GeV/nucleon to just above 1 GeV/nucleon. The Cherenkov counters employed silica-aerogel radiators with indices of refraction n=1.14, corresponding to an energy threshold of ~1 GeV/nucleon. Thus, the velocity measurement from the Cherenkov counters complements and extends the energy range covered by the TOF. We discuss improvements to the mass resolution above Cherenkov threshold and present results for the ^{10}Be/^{9}Be and ^{7}Be/Be ratios in the energy range covered by the Cherenkov counters (1.1-2.0 GeV/nucleon).

1 Introduction

Galactic cosmic rays (GCRs) propagate through the Galaxy occasionally interacting with the interstellar medium to produce a secondary population not normaly found at cosmic ray sources. While secondary isotopes constrain the pathlength distribution of GRCs traversing the interstellar medium (ISM), radioactive species provide information on the time between events during the GCR lifetime. A particular class of secondary isotopes that decay through the β-decay channel offer important constraints on the size of the confinement volume, the duration of propagation within the volume, and on the average interstellar density. These radioactive isotopes, ^{26}Al, ^{36}Cl, ^{54}Mn, ^{14}C, and ^{10}Be, serve as propagation "clocks". Recent observations from experiments on-board spacecraft such as Ulysses and the Advanced Composition Explorer (ACE) have been able to detect these radioactive clocks between ~40-400 MeV/nucleon with high statistical accuracy.

Models of cosmic-ray propagation strive to interpret these observations in the context of cosmic-ray confinement within our Galaxy. Recent predictions from the standard Leaky Box Model (LBM) by Yanasak et al. (1999), derive a confinement time of $\sim 1.5 \times 10^7$ yrs and an average interstellar density of ~0.3 H atoms/cm^3 based on measurements from ACE. More complex models of propagation account for structure within the confinement volume such as the Diffusion Halo Model of Simon & Molnar (1999) and the diffusion models of Moskalenko & Strong (2000) and Ptuskin (1998). The calculations of Ptuskin (1998) interpret current measurements in terms of the local ISM inhomogeneities and the constraints placed on the diffusion coefficient. Indeed, the slightly different half-lives of these radioactive species limit the region of space traversed prior to decay, providing very different samples of the local ISM. The radioactive isotope, ^{10}Be, having the largest half-life ($\sim 1.6 \times 10^6$ yrs), samples the largest local ISM volume, perhaps offering a more representative average of the ISM density. Furthermore, at relativistic energies, time-dilation extends the decay lifetime of these isotopes, making the longest lived ^{10}Be isotope an ideal probe of the mean age distribution of cosmic rays and further constraining propagation models.

The Isotope Magnet Experiment (ISOMAX) was designed to measure the light isotopes from $3 \leq Z \leq 8$ with a particular emphasis on the measurement of the radioactive isotope ^{10}Be up to relativistic energies for the first time. In order to obtain excellent mass resolution and the desired large aperture, ISOMAX employed three detector subsystems, a state-of-the-art time-of-flight (TOF) system, a superconducting magnetic spectrometer, and two silica-aerogel Cherenkov detectors (Mitchell et al. 1999; Hof et al. 2000). ISOMAX had its first high-altitude balloon-borne flight in August 1998 from Lynn Lake, Manitoba, Canada. During the ISOMAX flight, 13 hours of data were collected at a residual atmo-

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sphere of less than 5 g/cm^2 with an additional several hours at lower altitudes. The overall geometry factor for ISOMAX is ~450 cm^2sr for the TOF and DC and is reduced according to the active area of the Cherenkov counters. We present results from the 1998 flight, focusing on the analysis in the high-energy range covered by the Cherenkov counters.

2 Instrumentation & Flight Performance

ISOMAX was designed to measure particle mass using the velocity-rigidity technique. The rigidity was obtained from a measure of the particle curvature through the magnetic spectrometer. During the 1998 flight, ISOMAX achieved excellent spatial resolution (~45 μm for beryllium) and a maximum detectable rigidity (MDR) of ~1.2 TV for beryllium events. The velocity was obtained in two separate but overlaping energy ranges from the TOF system for energies below ~1 GeV/nucleon and from two Cherenkov counters for energies above the radiator threshold of ~1.08 GeV/nucleon. The TOF system consists of three separate layers of Bicron BC420 scintillators with a timing resolution of 60 psec for beryllium. All three layers of the TOF were used to provide an unambiguous identification of particle charge. A detailed description of the identification of particle mass below 1 GeV/nucleon using the TOF system is described elsewhere in these proceedings (Hams et al. 2001). The ISOMAX results for isotopes of lithium will be presented in an additional paper in these proceedings (Göbel et al. 2001).

Above ~1 GeV/nucleon the Cherenkov counters were used to determine particle velocity. The counters were large area, diffusive-light-integration counters viewed by 16 photomultiplier tubes per counter. Each counter consisted of two radiator layers. The radiators were configured in a 2x2 matrix of silica-aerogel blocks, with an approximate block size of 38x38x2 cm^3. The aerogel radiators have an index-of-refraction of ~1.14 which corresponds to a energy threshold of 1.08 GeV/nucleon. For a detailed discussion of the counter performance refer to de Nolfo et al. (1999).

3 Response and Index Mapping of Cherenkov Counters

The mass resolution in the energy range covered by the Cherenkov counters is dominated by the uncertainty in the velocity measurement. Several factors contribute to the velocity resolution including photoeletron statistics, response map variations, refractive index variations, and the uncertainty in the contribution from knock-on electrons. For both counters, the total light yield was 22 photoelectrons for singly charged, relativistic particles. Response maps for the aerogel radiators in both counters have been generated from 48 hours of ground-muon data (de Nolfo et al. 1999). Variations in the detector response are less than 20%, with the largest variations occuring toward the edges of the detector. We have chosen a conservative active area of the detector to reduce the overall corrections for response variations to less than 7%. In addition, these response maps were compared with

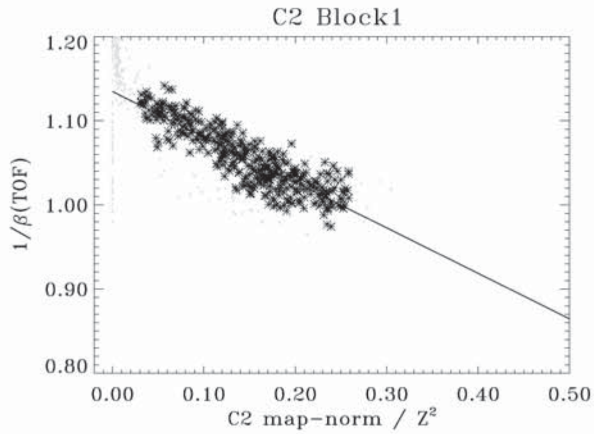

Fig. 1. $1/\beta_{TOF}$ versus C2 map-normalized signal divided by the square of the charge for beryllium, carbon, and oxygen events. The y-intercept gives the index-of-refraction ($n = 1/\beta$).

response maps from in-flight helium events for consistency.

The trigger thresholds were set to be efficient for lithium while at the same time eliminating most of the abundant proton and helium events. Consequently, only a limited number of helium events are available to determine the response map and variations in the index-of-refraction from in-flight data. A number of methods were explored to determine the variations in refractive index from radiator block to block. The refractive index was varied until a gaussian fit to the peaks of the reconstructed mass histograms for helium events resulted in peak locations corresponding to the isotopic helium masses 3 and 4. In addition, the refractive index was reconstructed using in-flight beryllium, carbon, and oxygen events. Though fewer in number, Be, C, and O nuclei have a greater light yield (yield $\propto Z^2$) and thus an improved velocity resolution compared with helium events. For this method, variations in the refractive index are determined by fitting a straight line to the velocity obtained from the TOF system ($1/\beta_{TOF}$) versus the map-normalized signal from a particular layer (consisting of two blocks, one on top of the other). Figure 1 shows an example of the fit for one of the two-block layers located in the second Cherenkov counter. The y-intercept determines the refractive index. These fits are performed for all four two-block layer sets in each of the two counters. The difference between using He to map the refractive index rather than Be, C, and O events is less than 0.3%. In addition, the refractive index can be compared with the index derived from measurements of the radiator density since the refractive index, n, is related to the aerogel density by the experimentally-determined formula $n - 1 = 0.21\rho$ (Poelz & Riethmüller 1982). Block to block variations in the refractive index are less than 5% and have been accounted for using the in-flight helium data.

4 Data Analysis

We employ several selection criteria in order to ensure a clean sample of events. The data set is limited to altitudes with a residual atmosphere of less than 5 g/cm^2 in order to minimize the effects due to the overlaying atmosphere. Events must meet the criteria for a successful track reconstruction with the magnetic spectrometer. Eight of the sixteen layers in the bending direction and four of the eight layers in the non-bending direction are required for a successful track reconstruction. Unambiguous charge identification is accomplished with the requirement that all three layers of the TOF provide a consistent measure of the particle charge. Events that interact within the instrument are eliminated by employing the above selection criteria.

Background events or events near threshold that have large knock-on fluctuations are removed by demanding consistency between the two Cherenkov counters. A correlation probability based on Poisson statistics can be formed between the two counters (Labrador 1996). In addition, since the TOF covers an overlaping energy range to that of the Cherenkov counters, a correlation between the total light yield from the two counters and the velocity determined from the TOF also helps to identify spurious events perhaps due to poor track reconstruction. After applying the above selection criteria, 94 beryllium events remain between 1.1 and 2.0 GeV/nucleon.

Figure 2 shows the velocity determined from both Cherenkov counters (the weighted mean of the velocity determined from the top and bottom counters) versus the rigidity determined from the magnetic spectrometer for beryllium events during the flight. The isotopes of ^{7}Be, ^{9}Be, and ^{10}Be are clearly resolved. The corresponding mass histograms are

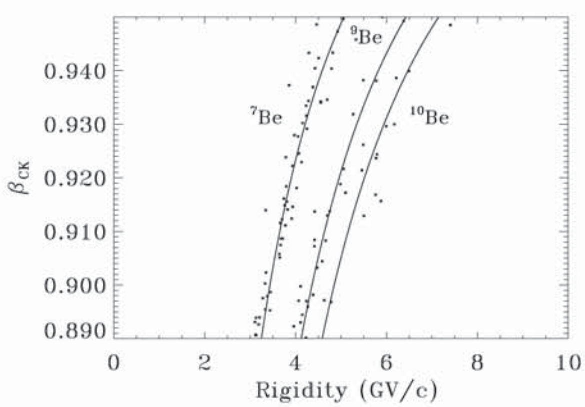

Fig. 2. Velocity determined from the Cherenkov counters (β_{CK}) versus rigidity for beryllium events obtained during the flight.

shown in Figure 3 between 1.1 and 2.0 GeV/nucleon. An instrument simulation, originally developed for IMAX, has been updated for the ISOMAX configuration, incorporating the experimentally derived TOF timing resolution of ISOMAX, the spectrometer MDR of $\sim$1.2 TV, the spatial resolution of 45 μm for beryllium, and the total light yield from the two Cherenkov counters of 22 photoelectrons derived from ground-muon data. The effect of knock-on contributions to the total light yield of the Cherenkov counters, modeled after the work of Grove & Mewaldt (1992), has also been included in the simulation. The number of events under the ^{10}Be and ^{9}Be mass peak is determined by a χ^2- minimization technique between the data and the simulation where the ^{10}Be/^{9}Be ratio is the free parameter. The fit is shown in Figure 3 as the dashed curve, resulting in a ^{10}Be/^{9}Be ratio of 0.349 ± 0.125 at the instrument.

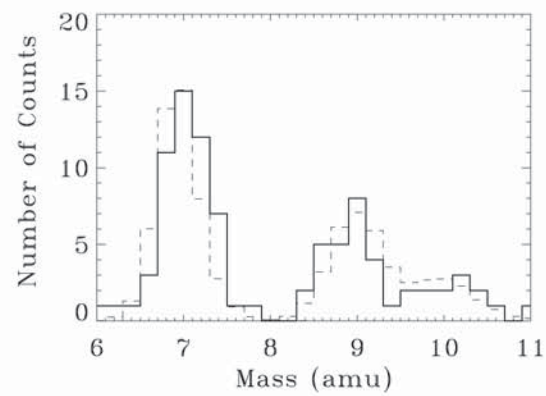

Fig. 3. Mass histogram for beryllium isotopes between 1.1 and 2.0 GeV/nucleon obtained during the flight. The dashed curve represents a fit to the data from an instrument simulation.

The ^{10}Be/^{9}Be ratio has been corrected for loss due to interactions within the instrument, which has a total grammage of 11.2 g/cm^2. A correction due to the effects of 4.6 g/cm^2 of residual atmosphere is determined based on an atmospheric propagation model. The model assumes primary spectra from the measurements by Englemann et al. (1990) and from ACE/CRIS, demodulated into interstellar (IS) abundances. A Leaky Box model with an ISM density of 0.3 atoms/cm^3 was used to derive an initial ^{9}Be spectrum at the top of the atmosphere. For ^{10}Be, we assume a similar spectral shape to that of ^{9}Be. An overall solar modulation level of ϕ = 430 MV is chosen to account for the level of modulation experienced by ISOMAX in 1998. These modulated spectra are then propagated through the atmosphere. The model incorporates the partial cross sections of Silberberg et al. (1998) and Tsao et al. (1998) and the total inelastic cross sections from Kox et al. (1987). After instrument and atmospheric corrections, the resulting ^{10}Be/^{9}Be ratio is 0.31 ± 0.11 between 1.12 - 2.02 GeV/nucleon at the top of the atmosphere. Errors represent the statistical uncertainty only. We are currently investigating the additional uncertainty introduced by the instrumental and atmospheric corrections.

5 Results and Discussion

Figure 4 shows the ^{10}Be/^{9}Be ratio measured above 1 GeV/nucleon compared with previous measurements at several 100 MeV/nucleon from SIS/CRIS on ACE, IMP 7 & 8, Voyager 1 & 2, Ulysses, and ISEE-3. The low energy ISOMAX measurement between 0.261 and 1.030 GeV/nucleon (in the TOF range) is also shown in Figure 4 and is discussed in

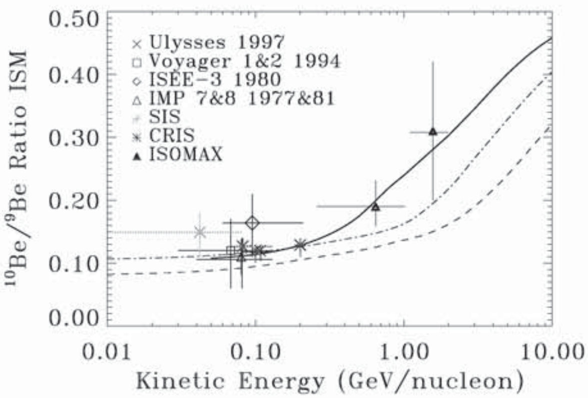

Fig. 4. ^{10}Be/^{9}Be ratio compared with previous measurements of Ulysses (Connell et al. 1998), Voyager 1 & 2 (Lukasiak et al. 1997), ISEE-3 (Wiedenbeck & Greiner 1980), IMP 7 & 8 (Garcia-Munoz et al. 1977, Garcia-Munoz & Wefel 1981), and ACE (Yanasak et al. 1999). See text for discussion of propagation models shown. ISOMAX errors represent statistical uncertainty only.

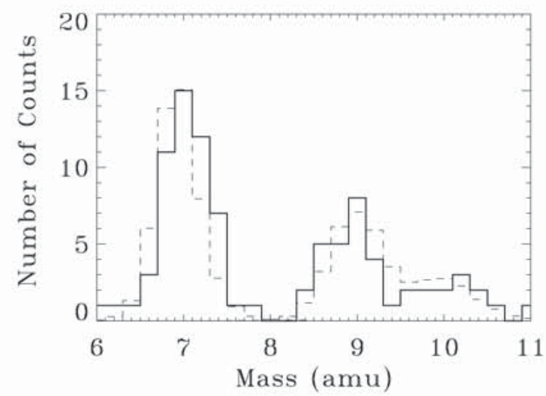

Fig. 5. ^{7}Be/Be ratio compared with previous measurements from Buffington et al. 1978, Webber et al. 1971 and previous spacecraft observations. The dashed curve represents a diffusion model with halo size of 4 kpc (Strong & Moskalenko 2001).

detail in these proceedings (Hams et al. 2001). The solid curve in Figure 4 is the prediction of a Leaky Box model by Yanasak et al. (2001) assuming an average interstellar density of 0.34 atoms/cm^3. The dashed-dot curve is the prediction of a Leaky Box model by Molnar & Simon (2001) assuming an ISM density of 0.23 atoms/cm^3. Finally, the dashed curve represents the predictions of a diffusion model by Moskalenko & Strong (2000) for a galactic halo size of 4 kpc and takes into account the local galactic structure and results from other spectroscopic observations. The statistical uncertainties of the ISOMAX results, in combination with the spread in model predictions, preclude any final conclusions concerning cosmic-ray propagation at present. A detailed survey of different model assumptions may help to clarify some of the ambiguity.

Figure 5 shows the ^{7}Be/Be ratio at the top of the atmosphere in two separate energy ranges (covered by the TOF and the Cherenkov counters) compared with the previous measurements of Buffington et al. (1978), Webber et al. (1971), and more recent spacecraft observations. ISOMAX is not consistent with the previously observed energy dependence of Buffington et al. (1978) suggesting the onset of K-capture and decay for ^{7}Be at about 500 MeV/nucleon.

6 Conclusions

ISOMAX has made the first measurements of the ^{10}Be/^{9}Be ratio above 1 GeV/nucleon. Despite the limited statistics, ISOMAX results appear to favor a rapidly rising ratio, which places some constraints on model parameters and processes such as reacceleration. Future experiments designed to measure the ^{10}Be/^{9}Be with improved statistics will help to distinguish between various propagation models, placing further constraints on our understanding of the local galactic structure and the cosmic-ray diffusion coefficient.

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References

ACE, on-line CRIS Level2 Data, California Inst. of Tech., 2000.
Buffington, A., et al., Ap.J., 226, 355, 1978.
Connell, J.J., et al., Ap.J., 501, L59, 1998.
de Nolfo, G.A., et al., Proc. 26th ICRC,3, 29, 1999.
Englemann, J.J., et al., A& A, 233, 96, 1990.
Garcia-Munoz, M., et al., Ap.J., 217, 859, 1977.
Garcia-Munoz, M., & Wefel, J.P., Proc. 17th ICRC,2, 72, 1981.
Göbel, H., et al., these proceedings, 2001.
Grove, J.E., & Mewaldt, R.A., Nuc. Instr. & Meth., A 314, 495, 1992.
Hams, T., et al., these proceedings, 2001.
Hams, T., et al., Proc. 26th ICRC,3, 121, 1999.
Hof, M., et al., Nuc. Instr. & Meth., A 454, 180, 2000.
Kox, S., et al., Phys. Rev. C, 5, 1678, 1987.
Labrador, A., Ph.D. Defense, Caltech, Pasadena, CA, 1996.
Lukasiak, A., et al., Proc. 25th ICRC,3, 389, 1997.
Mitchell, J.W., et al., Proc. 26th ICRC,3, 113, 1999.
Molnar, A. & Simon, M., Proc. of 27th ICRC, OG 1.3, 2001.
Moskalenko, I., & Strong, A.W., Astrophys. & Space Science, 272, 247-254, 2000.
Poelz, G., & Riethmüller, R., Nucl. Instr. & Meth. in Phys. Res., 195, 491, 1982.
Ptuskin, V.S., & Soutoul, A., A & A, 337, 859-865, 1998.
Silberberg, R., et al., Ap.J., 501, 911, 1998.
Simon, M., & Molnar, A., Proc. 26th ICRC,4, 211, 1999.
Strong, A. W., & Moskalenko, I. V., Adv. Sp. Sci., in press, astro-ph/0101068, 2001.
Tsao, C.H., et al., Ap.J., 501, 920, 1998.
Webber, W.R., et al., Ap.J. Lett., 18, 125, 1977.
Wiedenbeck, M.E., & Greiner, D.E., Ap.J., 239, L139, 1980.
Yanasak, N., et al., Proc. 26th ICRC, 3, 9, 1999.
Yanasak, N.E., submitted for publication to ApJ, 2001.